Treatment of Diesel Exhaust by a Diesel Particulate Filter Enhances Lung Inflammation.

Subramanian Karthikeyan[1], Errol Thomson[1], Prem Kumarathasan[1], Josee Guenette[1], Debbie Rosenblatt[2], Tak Chan[2], Greg Rideout[2], Renaud Vincent[1].

[1]Environmental Health Science and Research Bureau, Research and Radiation Directorate, Health Canada; [2]Emission Research and Measurements Section, Air Quality Research Division, Science and Technology Branch, Environment Canada

Extended Summary

Traffic-related air pollution is associated with adverse health effects. Epidemiological studies have shown effects within a few hours after a rise in the level of air pollution (1-3). Emission standards have been made increasingly stringent in an effort to curb traffic-related air pollution. For example, during the period from 2006-12, the North American heavy-duty vehicle emissions standards will fall by as much as 90%. Regulated NO_X and particulate matter (PM) concentrations will be reduced to 0.2, and 0.01 g/hp-hr respectively from their previous levels (www.dieselnet.com). The Euro VI standard that will come to effect in 2013 will require the same stringency for PM emissions. Emission reduction requires novel engine designs, exhaust treatment technologies and fuel formulations. However, the use of new fuel formulations and vehicle technologies will inevitably alter emission chemistry and consequently toxicity. This work was aimed at understanding the biological impacts of acute exposure to diesel exhaust and evaluating the impact of particulate emission reduction through application of a diesel particulate filter (DPF).

Specific pathogen-free Fisher rats (male, 250 g) were exposed by inhalation for 4 hours to dilute diesel exhaust from a heavy-duty diesel engine (model year 2004 Cummins ISM 280, 10.8 L, inline 6 cylinder, 280 bhp @ 2100 rpm, 2004 emission standard). The engine was operated in a steady state condition using an engine dynamometer and a constant volume sampling system (CVS). The first configuration for testing was engine out (EO) and involved operating the engine with no exhaust treatment system. For the second configuration, a catalyzed passive regenerating diesel particulate filter (DPF) was installed on the engine. The engine was pre-conditioned to ensure oil and cooling fluid temperatures were stabilized, and was then operated continuously for 4 hours (1200 rpm @ 150 bhp, 650 ft-lb torque). Commercial ultra low sulphur diesel was used to power the engine. Particle size distribution analyses were conducted using an Engine Exhaust Particle Sizer (TSI Inc, USA). Particle mass concentration was monitored using a DustTrack II DRX (TSI). Animal exposures (n=8/group) were conducted in whole body inhalation chambers at a flow rate of 15 chamber volume per hour. Exposures to diluted exhaust (EO configuration) and to exhaust treated by a diesel particulate filter (DPF configuration) were conducted on two separate weeks with clean air chamber controls (HEPA filtered air) and naïve (unexposed) animals as controls during each week. Necropsies were conducted either 2 or 20 hours after inhalation exposures.

The diesel particle filter removed most of the CO (EO vs DPF, 6.1 vs 1.2 ppm) and hydrocarbons (10 vs 3 ppm), and virtually eliminated particulate mass (269 vs <2 $\mu g/m^3$). In contrast, NO_2 was increased 4-fold by DPF (4 vs 16 ppm) (Table 1). Particle count concentration in the inhalation chamber was 1.3 x $10^6/cm^3$ for the EO configuration, with a count median diameter of 50-70 nm. Deployment of the DPF eliminated the 50-70 nm size mode, but produced an ultrafine mode at 8-10 nm in the test atmosphere with a particle count of 1.6 x $10^6/cm^3$ (Figure 1). Therefore, the deployment of the DPF reduced particle mass concentration, but created an ultrafine mode in the nano scale and increased NO_2 emission. Exposure to diesel exhaust caused an influx of neutrophils in the lungs, the response being enhanced in the animals exposed in the DPF configuration (Figure 2). Diesel exhaust exposure also increased expression of the inflammatory genes IL-6, TNF-α, PTGS2, and the stress response gene MT2a, but not the xenobiotic response gene CYP1A1. Gene expression changes were also enhanced in the DPF configuration by comparison to the EO configuration. There were minimal differences between naïve unexposed animals and HEPA air chamber control animals, indicating that the biological responses were not related to stress of chamber confinement or transport of the animals between the holding facility and the emission testing environment.

Table 1. Exposure Atmospheres (Engine Out and Diesel Particulate Filter)

Treatment	Engine			Dilution Tunnel Concentrations						Exposure Chamber				
	Speed (rpm)	Torque (lb-ft)	Power (bhp)	CO (ppm)	CO_2 (%)	NOx (ppm)	NO (ppm)	NO_2 (ppm)	HC (ppm)	CO (ppm)	NOx (ppm)	NO (ppm)	NO2 (ppm)	Mass ($\mu g/m^3$)
EO	1201	650	149	6.4	0.9	49	45	4	10	6.1	48	44	4	269
DPF	1200	638	146	1.2	0.9	37	21	16	3	1.2	36	20	16	<2

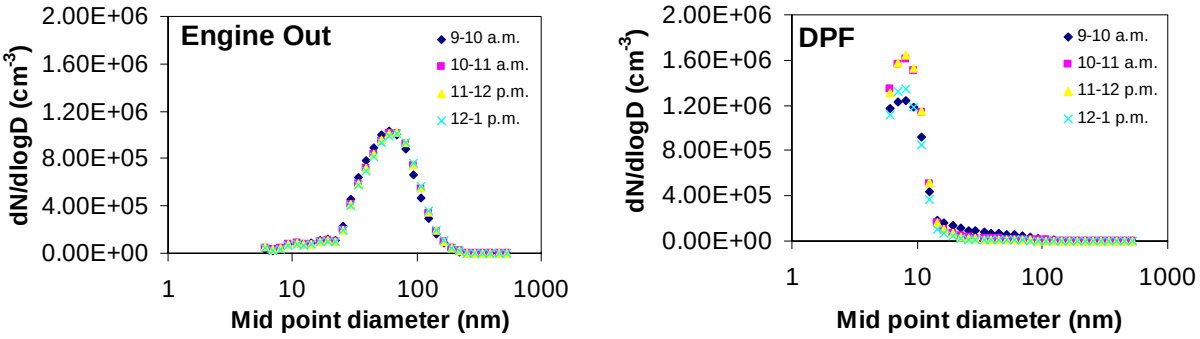

Figure 1. Particle Size Distributions During Diesel Exhaust Exposures

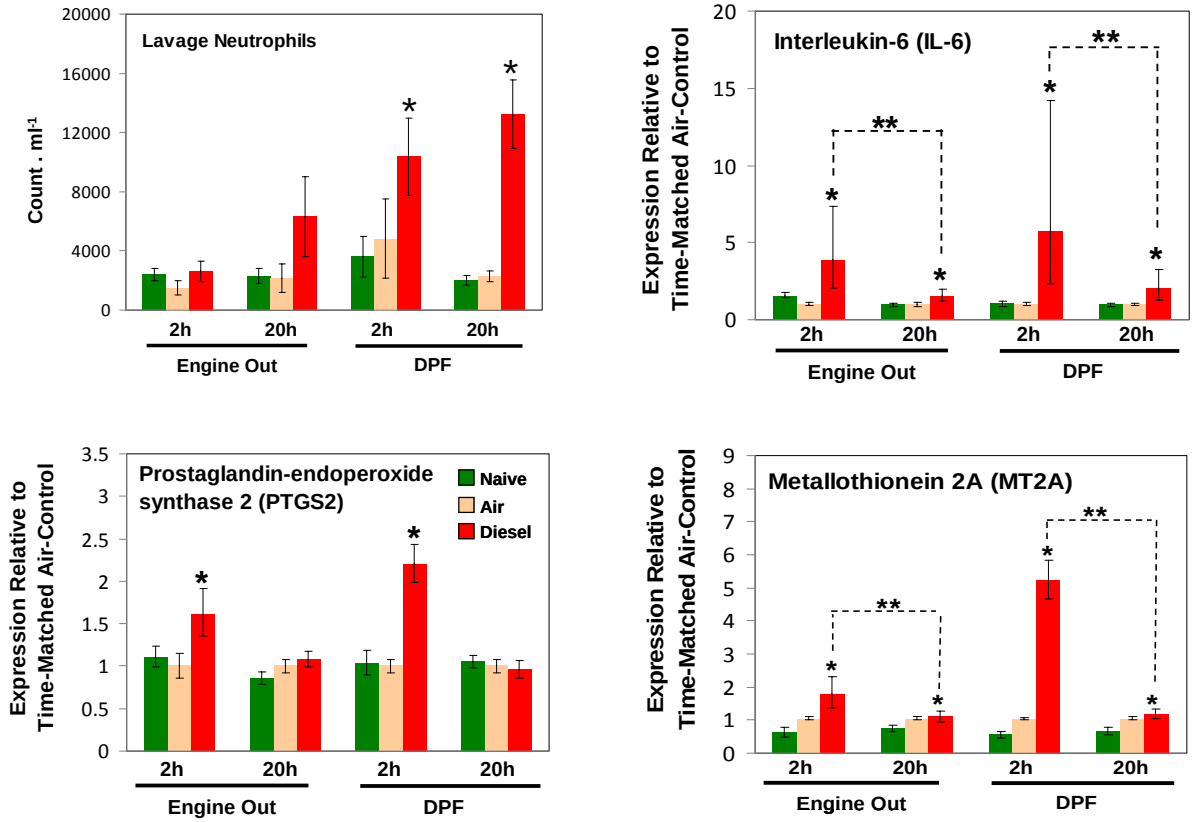

Figure 2. Biological impacts of diesel exhaust exposure: inflammatory (neutrophil infiltration, IL-6 and PTGS2 gene expression) and oxidative stress (MT2A gene expression) responses accentuated by DPF configuration. Significant ($p<0.05$) effects of diesel are indicated in the figure (* diesel vs air, naïve within a given treatment, ** 2 vs 20 h within diesel; Analyzed by 3-way ANOVA with Treatment (EO, DPF), Exposure (Naïve, Air, Diesel) and Recovery (2h, 20h) as factors.

Nitrogen dioxide is a strong oxidative air pollutant and its role as a mediator of inflammatory response characterized by neutrophilia is well established (4,5). Therefore, the enhanced inflammatory and oxidative stress responses to diesel exhaust treated by diesel particulate filter (DPF configuration) is in line with the 4-fold increase in NO_2 emission, despite virtual elimination of particulate mass (269 $\mu g/m^3$ vs <2 $\mu g/m^3$). However, reduction in mass concentration was accompanied by the apparent bleeding of ultrafine particles (8-10 nm) from the DPF. It is not possible in our experiment to discount a potential role of these ultrafine particles in the enhancement of the biological responses. Elimination of the ultrafine mode through HEPA filtration should help resolve the relative contributions of PM and gases to the toxicity of emissions.

Our study reveals some of the difficulties in disentangling the effects of specific constituents of complex emissions, particularly when testing emission control technologies that alter multiple constituents. Alternative experimental approaches may be necessary to decompose factor interactions and elucidate the major determinants of toxicity.

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Traffic Related Air Pollution

Asthma, Cardiovascular disease, Cancer etc.

Stringent Vehicle Emission Standards

Heavy Duty Diesel Highway Engine Standards (USA/CANADA)		
Model Year	**PM (g/bhp-hr)**	**NOx (g/bhp-hr)**
1988	0.6	10.7
1998	0.05	4
2004	0.05	2
2007	0.01	0.2

Fuel Sustainability

Advanced Fuels

Biodiesel, Bioethanol, Biomass-to-Liquids (Fisher-Troph fuels) etc.

Novel Combustion Technologies

Advanced Fuel Injection, Lean Burn Combustion, Exhaust Gas Recirculation etc.

Emission Control Technologies

Selective Catalytic Reduction, Diesel Particulate Filter, Diesel Oxidation Catalyst etc.

Unknown Emission Chemistry

Unknown Toxicity and Health Effects

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Experimental Design:

Animals: Healthy, male, Fisher rats, average weight 250g, n=8/group.

Exposure: Inhalation route, whole-body exposure chambers, 4 hour exposure to whole diesel exhaust generated under steady state operation of a heavy-duty diesel engine (1200 rpm @150 bhp, 650 lb-ft torque) using commercial ultra low sulphur diesel.

Experiments were conducted during two separate weeks

Week 1 (Engine operation in the engine out configuration)

- Diesel exposure, Air exposure, Naïve unexposed animals

Week 2 (Engine operation with diesel particulate filter)

- Diesel exposure, Air exposure, Naïve unexposed animals

Recovery after exposure: 2 h and 20h after exposure

Endpoints: Cardiovascular, oxidative and inflammatory responses

Data Analysis: Three-way ANOVA with Treatment (EO, DPF), Exposure (Naïve, Air, Diesel) and Recovery (2h, 20h) as factors.

Rationale:

We are currently involved in the toxicity testing of matrices of fuels, engines, runs cycles, and emission treatment technologies (including diesel particulate filter).

Our past experimental data have established a linkage between acute exposure to ambient particulate matter and cardiovascular effects.

Application of a diesel particulate filter would enable testing biological impacts of diesel exhaust particulate matter in whole exhaust exposures.

Objectives

To understand the biological impacts of acute exposure to diesel exhaust

To understand the role of the particulate constituent in eliciting these effects by application of a diesel particulate filter

Inhalation Exposures:

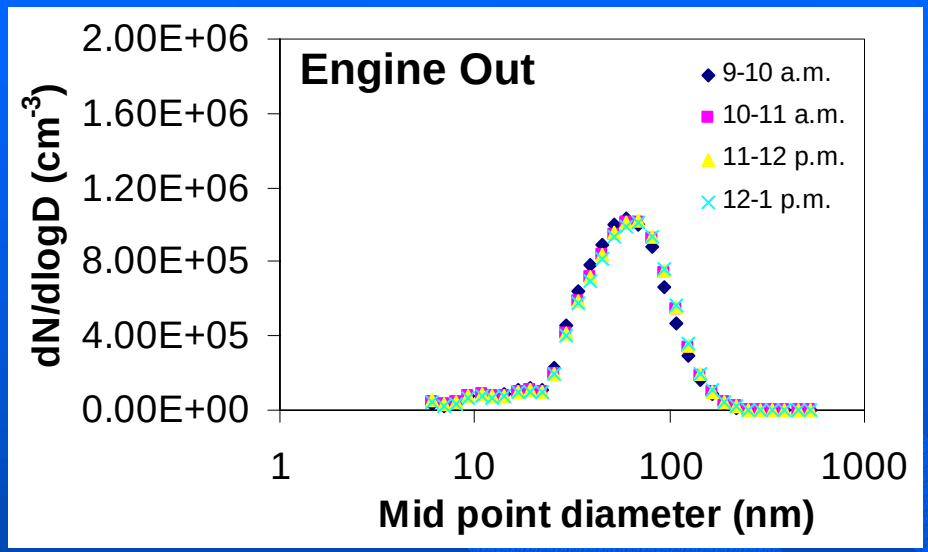
Engine

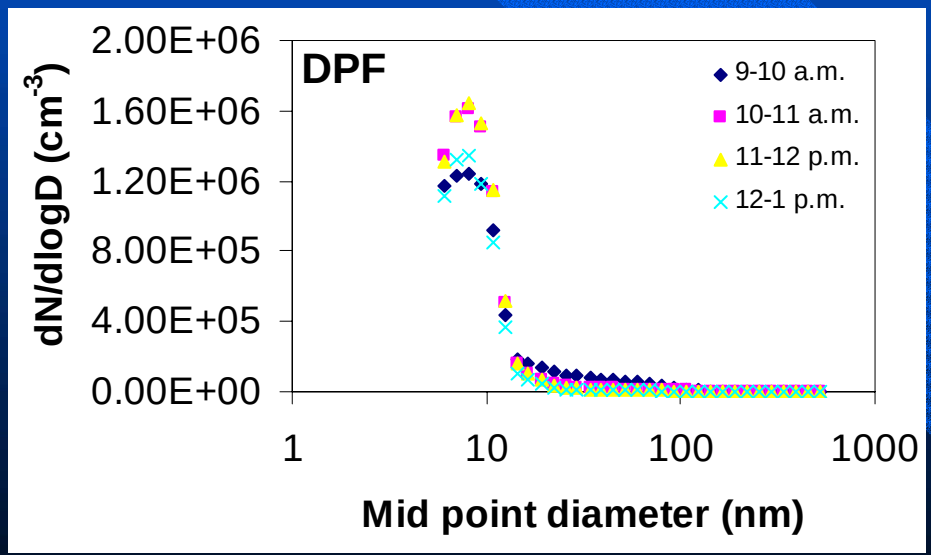
Heavy-duty diesel engine; Model Year 2004 Cummins ISM 280, 10.8 L, inline 6 cylinder, 280 bhp @ 2100 rpm, 2004 emission standard.

Diesel Particulate Filter:

A catalyzed passive regenerating diesel particulate filter (DPF).

Exposure Characterization (Particulate Matter):





Treatment	Mass (µg/m^3)
EO	269
DPF	<2

DPF Configuration resulted in:

Elimination of a 50-70 nm size mode, generation of a 8-10 nm ultrafine mode

Virtual elimination of particulate mass

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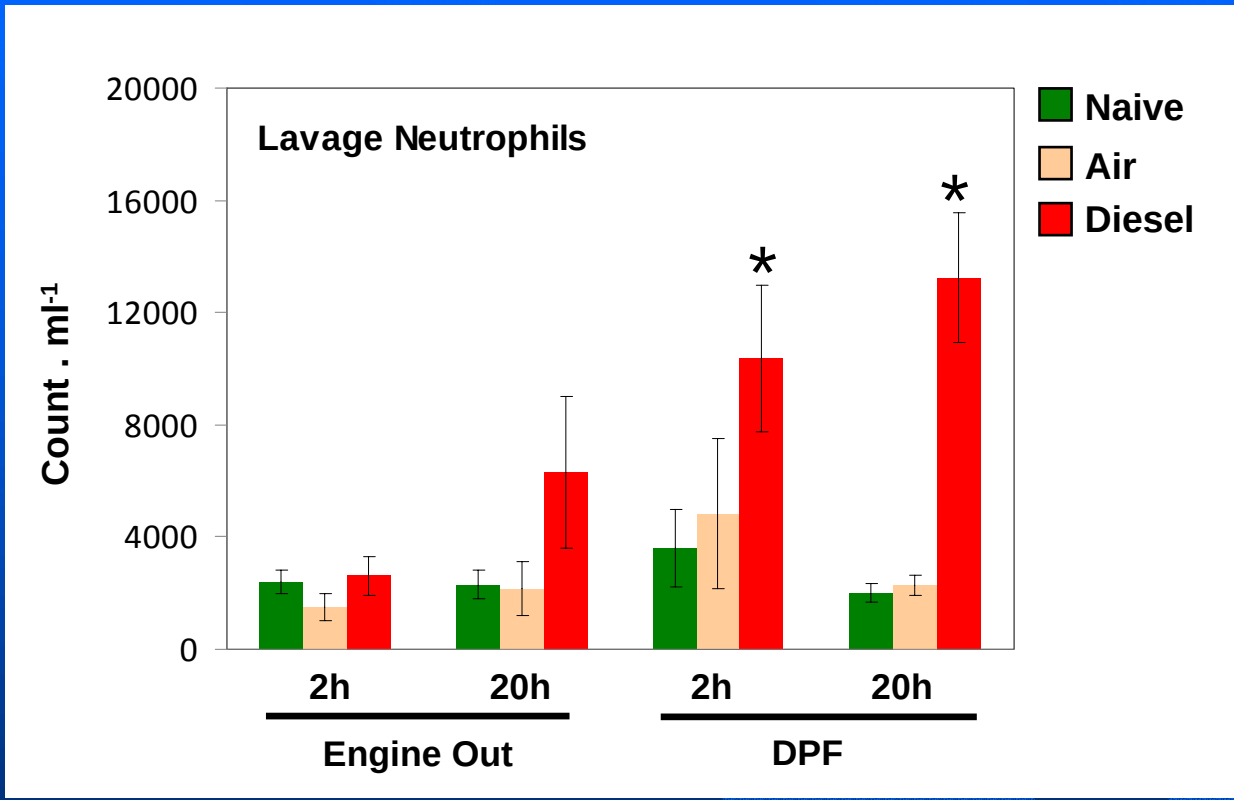
Exposure Characterization (Gaseous Components):

Treatment	Dilution Tunnel						Exposure Chamber			
	CO_2 (%)	CO (ppm)	NOx (ppm)	NO (ppm)	NO_2 (ppm)	HC (ppm)	CO (ppm)	NOx (ppm)	NO (ppm)	NO_2 (ppm)
EO	0.9	6.4	49	45	4	10	6.1	48	44	4
DPF	0.9	1.2	37	21	16	3	1.2	36	20	16

DPF Configuration resulted in:

Reduction of CO, total NOx, and HC, but a 4-fold increase in NO_2

Acute Lung Inflammation:



Elevated neutrophil response at 20h with diesel exhaust in the engine out configuration

DPF treated exhaust exposure resulted in an early, sustained and enhanced enhanced response.

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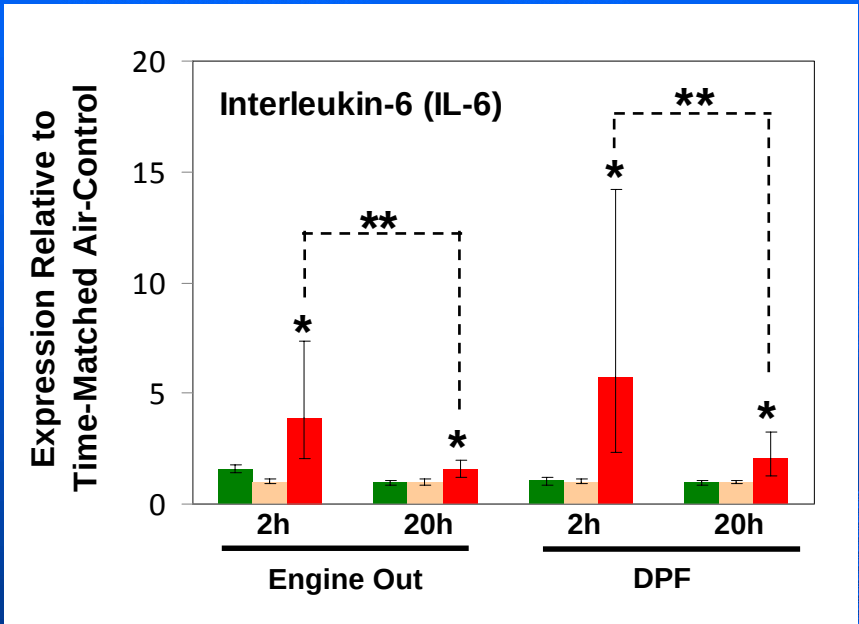
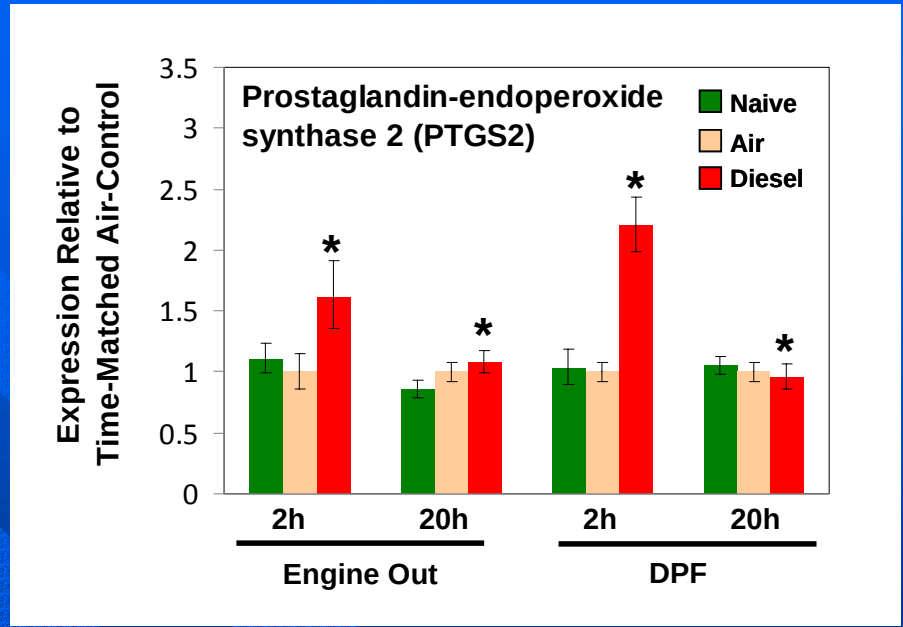
Inflammatory Gene Responses:





Interleukin-6 and PTGS2 (COX-2, cyclooxygenase) were both elevated 2h post exposure.

Effect sizes were larger with DPF exposure.

Effects were reduced (IL-6) or disappeared (PTGS2) at 20h after exposure.

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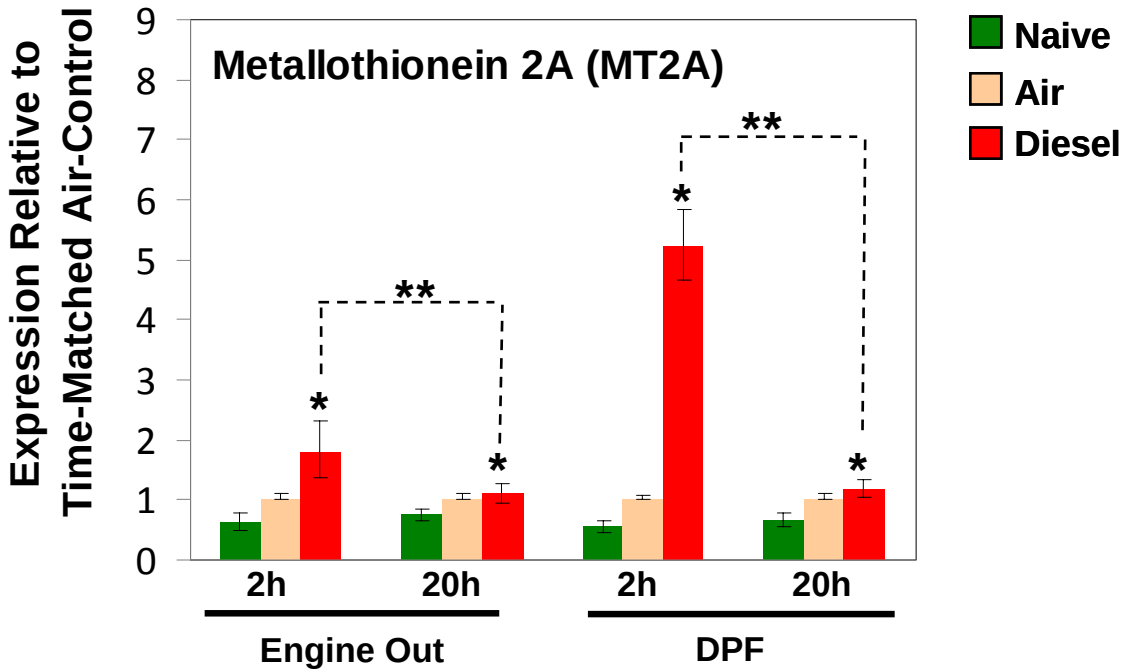
Oxidative Stress Response:



Early elevation similar to other inflammatory markers (IL-6 and PTGS2)

Enhanced response to DPF treatment.

Effect subsides at 20h after exposure.

Conclusions:

Enhanced inflammatory and oxidative stress responses in the DPF exposure is in line with the 4-fold increase in NO_2 emission, despite virtual elimination of particulate mass (269 µg/m^3 vs <2 µg/m^3).

A role of the ultrafine mode in the enhancement of the biological responses cannot be discounted.

Elimination of the ultrafine mode through HEPA filtration should help resolve the relative contributions of PM and gases to the toxicity of emissions.

Difficulties in disentangling effects of specific constituents of complex emissions need to be addressed.

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